

# Antimatter from the cosmological baryogenesis and the anisotropies and polarization of the CMB radiation

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We discuss the hypotheses that cosmological baryon asymmetry and entropy were produced in the early Universe by phase transition of the scalar fields in the framework of spontaneous baryogenesis scenario. We show that annihilation of the matter-antimatter clouds during the cosmological hydrogen recombination could distort of the CMB anisotropies and polarization by delay of the recombination. After recombination the annihilation of the antibaryonic clouds (ABC) and baryonic matter can produce peak-like reionization at the high redshifts before formation of quasars and early galaxy formation. We discuss the constraints on the parameters of spontaneous baryogenesis scenario by the recent *WMAP* CMB anisotropy and polarization data and on possible manifestation of the antimatter clouds in the upcoming *Planck* data.

## INTRODUCTION

Recent release of the first-year *WMAP* data has confirmed that our Universe is non-baryonic dominated. The vast collection of stars, galaxies and clusters nevertheless contains a huge amount of baryons without strong evidence of antibaryon contamination to the spectrum of electromagnetic radiation in the Universe. Does it mean that starting from the baryogenesis epoch all antibaryons, or more generally speaking, antimatter annihilate with the baryonic matter producing radiation and only relatively small amount of antibaryons can survive up to the present day during the expansion of the Universe? The answer to this question has been the point of discussions in the literature (see for review in [1, 2, 3, 4]) including the Big Bang Nucleosynthesis properties, antiprotons in the vicinity of the Earth and so on. The aim of this paper is to investigate antimatter contamination in the recent CMB data, namely, the *WMAP* anisotropy and polarization data through distortions of the hydrogen recombination kinetics and possible late reionization of the plasma and make the corresponding prediction for the future *Planck* mission.

We re-examine the baryogenesis models following the arguments by [1], in which the baryonic and antibaryonic matter are very non-uniformly distributed at very small scales (for example, the corresponding mass scale can be equivalent to  $M \sim 10^3 - 10^5 M_\odot$  [1] and follows the adiabatic perturbation upon these scales. Obviously, the possibility of having non-uniformly distributed baryonic fraction of the matter at very small scales is related to the Affleck-Dine baryogenesis [5] or the spontaneous baryogenesis mechanism [6]. Taking into account the electromagnetic cascades driven by proton-antiproton annihilation at the epoch of hydrogen recombination, we will show how they distort the kinetics of the recombination producing corresponding features in the CMB anisotropy and polarization power spectrum. Then we will discuss

possible late reionization of the hydrogen by the product of annihilation and the corresponding transformation of the CMB anisotropy and polarization power spectrum taking into account present *WMAP* and *CBI* observational data. Finally we will show that the upcoming *Planck* mission will be able to detect corresponding manifestation of matter-antimatter annihilation even if the well-known Sunyaev-Zeldovich  $y$ -parameter would be one order of magnitude smaller than the *COBE* FIRAS limit [7, 8, 9].

## BARYON-ANTIBARYON BUBBLE FORMATION IN THE UNIVERSE

It is assumed [1] that scalar baryon of SUSY model  $\xi$  is coupled to the scalar inflaton field  $\Phi$  by the following potential

$$V_{int}(\xi, \Phi) = (\lambda \xi^2 + h.c.) (\Phi - \Phi_{crit})^2, \quad (1)$$

where  $\lambda$  is the coupling constant and  $\Phi_{crit}$  is some critical value of the  $\Phi$  field, which determines the point of minimum of the  $V_{int}(\xi, \Phi)$  potential. Starting from the high values  $\Phi_{int} \gg \Phi_{crit}$  the inflaton field decreases down to  $\Phi_{crit}$  and  $V_{in}(\xi, \Phi)$  potential reach the point of minimum, while at  $\Phi \ll \Phi_{crit}$  for  $V_{int}(\xi, \Phi)$  potential we will have  $V_{int}(\xi, \Phi) = (\lambda \xi^2 + h.c.) \Phi_{crit}^2 = V(\xi)$  independently on the properties of the  $\Phi$  field. It has been shown [1, 2] that because of the properties of the interactions the most favorable conditions for baryogenesis might be created only for a short time scale. It corresponds to a relatively small spatial scales. Thus, the general picture of the baryonic matter-antimatter spatial distribution would be similar to random distribution of the islands with high baryon (or anti-baryon) asymmetry floating in the normal matter with  $\beta = n_{cmb}/n_b \simeq 5 \times 10^{-10}$ , where  $n_{cmb}$  and  $n_b$  are the present number densities of the CMB photons and baryons. The mass distribution function of the

baryon (anti-baryon) clouds (ABC) is also estimated [1]

$$\frac{dn}{dM} \propto \exp \left[ -\gamma^2 \ln^2 \left( \frac{M}{M_{\text{crit}}} \right) \right] \quad (2)$$

where  $\gamma$  and  $M_{\text{crit}}$  are free parameters of the theory. As one can see from Eq.(2), if  $\gamma \gg 1$  then the mass spectrum is localized at  $M \sim M_{\text{crit}}$ , while for  $\gamma \sim 1$  the mass spectrum will have monotonic character for the clouds distribution over wide range of masses. Dolgov and Silk [1] have also pointed out that  $M_{\text{crit}}$  could be close to the solar mass  $M_{\odot}$ , but the range of  $M_{\text{crit}}$  can be naturally expanded to  $10^3 - 10^5 M_{\odot}$  [2]. Let us assume that parameter  $\gamma$  has especially high value:  $\gamma \gg 1$  and the initial distribution function of the baryon-antibaryon clouds is close to the Dirac- $\delta$  function:  $dn/dM \propto \delta_D(M - M_{\text{crit}})$  and the characteristic size of clouds  $R_{cl} \propto M_{\text{crit}}^{1/3}$  is much smaller than the size of the horizon  $R_{\text{rec}}$  at the epoch of recombination ( $z \simeq 10^3$ ):  $R_{cl} \ll R_{\text{rec}}$ . We denote  $\rho_{b,\text{in}}$  and  $\rho_{b,\text{out}}$  the anti-baryon density inside and baryon density outside the clouds, respectively, and the mean density  $\rho_{b,\text{mean}}$  at the scales much greater than  $R_{cl}$  and distances between them,

$$\rho_{b,\text{mean}} = \rho_{abc,\text{in}} f + \rho_{b,\text{out}}(1 - f), \quad (3)$$

where  $f$  is the volume fraction of the clouds. We denote

$$\eta = \frac{\rho_{abc,\text{in}}}{\rho_{b,\text{out}}}. \quad (4)$$

We can write down the following relations between the mean value of the density and inner and outer values

$$\rho_{b,\text{in}} = \frac{\eta \rho_{b,\text{mean}}}{1 + f(\eta - 1)}, \quad (5)$$

and

$$\rho_{b,\text{out}} = \frac{\rho_{b,\text{mean}}}{1 + f(\eta - 1)}. \quad (6)$$

Using the functions  $f$  and  $\eta$  we can define the anti-baryonic mass fraction

$$F_b = \frac{\eta f}{1 + f(\eta - 1)}, \quad (7)$$

which is a function of the characteristic mass scale  $M_0$  of the anti-baryonic clouds.

Obviously, all the parameters  $f$ ,  $\eta$  and  $F_b$  are the results of the fine tuning of the inflaton  $V_{\text{in}}(\xi, \Phi)$  leading to the formation of baryonic asymmetry in the Universe.

## MATTER-ANTIMATTER BARYONIC CLOUDS IN THE HOT PLASMA

At the end of inflation the Universe became radiation-dominated by mostly light products of the inflaton decay. Some fraction of matter, however, can exist with

a form of primordial anti-baryonic clouds. Let us describe the dynamics of such ABC evaporation in the hot plasma. For simplicity we will further assume that a single ABC has spherically symmetric density distribution ( $\rho_{in} \equiv \rho_{in}(r)$ ) with the characteristic scale  $R$  starting from which the contact between ABC and the outer baryonic matter leads to energy release due to annihilation

$$\frac{dE}{dt} = 4\pi R^2 \varepsilon_{\text{out}} v_T = 4\pi R^2 c \varepsilon_{\text{out}} \left( \frac{3kT}{2m_p c^2} \right)^{1/2} \quad (8)$$

where  $v_T = (3kT/2m_p c^2)^{1/2}$  is the speed of sound in the plasma,  $\varepsilon_{\text{out}}$  is the energy density of the outer plasma,  $k$  is the Boltzmann constant,  $m_p$  is the proton mass and  $T$  is the temperature of the outer plasma. Using Eq.(8) and the energy of the inner ABC matter  $E_{cl} = M_{cl} c^2 \sim (4\pi R^3/3)\eta \varepsilon_{\text{out}}$  for the characteristic time of evaporation we get

$$\tau_{ev} \simeq \frac{E_{cl}}{dE/dt} = \frac{\eta R}{3c} \left( \frac{3kT}{2m_p c^2} \right)^{-1/2}. \quad (9)$$

Equation (9) indicates that any clouds with the size above  $R_{cr} \simeq (10^{-5} \div 10^{-4})\eta^{-1} (z/z_{\text{rec}})^{1/2} r_h(z_{\text{rec}})$  will survive up to the moment of the cosmological hydrogen recombination  $t_{\text{rec}} \simeq 2/3(\Omega_m H_0^2)^{-1/2} z_{\text{rec}}^{-3/2}$ , where  $z_{\text{rec}} \sim 10^3$  is the redshift of the recombination,  $H_0 = 100h$  is the present value of the Hubble constant,  $\Omega_m$  is the baryonic plus dark matter density scaled to the critical density and  $r_h(z_{\text{rec}})$  is the horizon at the moment of recombination. The baryonic mass at the moment of recombination is in order of magnitude  $10^{19} M_{\odot}$  [10] and the corresponding mass scale of the ABC should be roughly  $(10^4 \div 10^7 M_{\odot})\eta^{-3}$ . If the  $\eta$  parameter is close to unity, which means that density contrast between the inner and outer zones is small, then the corresponding mass scale of the ABC would be  $10^4 \div 10^7 M_{\odot}$ . However, if  $\eta \sim 10$ , the corresponding mass scale of the ABCs could be smaller, and comparable with the scale  $10 \div 10^4 M_{\odot}$ .

## ABC at the nucleosynthesis epoch

Let us compare the characteristic scales of the ABC with a few characteristic scales of process in the framework of the Big Bang theory. Firstly, the baryonic fraction of matter and its spatial distribution play a crucial role starting from the epoch when the balance between neutrinos ( $\nu_e, \bar{\nu}_e$ ), neutrons ( $n$ ) and protons ( $p$ ) in the following reactions  $n + \nu_e \leftrightarrow p + e^-$ ,  $n + e^+ \leftrightarrow p + \bar{\nu}_e$ ,  $n \rightarrow p + e^- + \bar{\nu}_e$  is broken. The corresponding time scale of violation of the neutrino-baryon equilibrium is close to  $\tau_{\nu_e, p} \simeq 1$  sec when the temperature of the plasma was close to  $T_{\nu_e, p} \simeq 10^{10} \text{K}$  (see for the review in [11]). The time scale  $\tau_{\nu_e, p}$  determines the characteristic length

$l_{\nu_e,p} \simeq c\tau_{\nu_e,p}$ , which in terms of the baryonic mass fraction of matter corresponds to

$$M_{\nu_e,p} \sim m_{pl} \left( \frac{\tau_{\nu_e,p}}{t_{pl}} \right) \left( \frac{\rho_b}{\rho_\gamma} \right) |_{t=\tau_{\nu_e,p}} \simeq 0.15(\Omega_b h^2) M_\odot, \quad (10)$$

where  $t_{pl}$  is the Planck time,  $\rho_b$  and  $\rho_\gamma$  are the densities of baryons and radiation in the standard cosmological model without anti-baryonic clouds. Following the SBBN theory we need to specify the moment  $\tau_{\text{end}}$  when all light elements (e.g.  $\text{He}^4$  and deuterium) were synthesized during cosmological cooling of the plasma. This moment is in order of the magnitude close to  $\tau_{\text{end}} \sim 3 \times 10^2 \div 10^3$  sec. In term of the baryonic mass scale it corresponds to

$$M_{\text{end}} \simeq M_{\nu_e,p} \left( \frac{\tau_{\text{end}}}{\tau_{\nu_e,p}} \right)^{3/2} \simeq 5 \times 10^3 \left( \frac{\tau_{\text{end}}}{10^3 \text{sec}} \right)^{3/2} (\Omega_b h^2) M_\odot. \quad (11)$$

Thus, if the characteristic mass scale  $M_0$  for the baryonic clouds is higher than  $M_{\text{end}}$ , the cosmological nucleosynthesis within each cloud and outside the clouds proceeds independently with others and the mean mass fraction of each chemical element would be the same as in SBBN theory. If all the anti-baryonic clouds will annihilate just before or after hydrogen recombination epoch, we will have simple renormalization of the baryonic matter density at the epoch of nucleosynthesis

$$\rho_{b,\text{out}} = \frac{\overline{\rho_b} + \rho_{abc} f}{1 - f} \quad (12)$$

where  $\overline{\rho_b}$  is the present day baryonic density rescaled to the SBBN epoch. As one can see from Eq.(12), if the fraction of the ABC is small ( $f \ll 1$ ), then all the deviation of the light-element mass fractions from the SBBN predictions would be negligible.

### ENERGY RELEASE TO THE COSMIC PLASMA FROM THE ABC AT THE EPOCH OF HYDROGEN RECOMBINATION

The net of ABC produce the net of the high energy photons because of annihilation at the boundary zones for each antimatter cloud. Using Eq.(8), we can estimate the rate of the energy injection to the plasma as

$$\frac{d\varepsilon}{dt} = \frac{dE}{dt} n_{cl} = \frac{\rho_{cl} c^2}{\tau_{ev}} \quad (13)$$

where  $\rho_{cl} = M_{cl} n_{cl}$  and  $n_{cl}$  is the spatial number density of the ABC. Let us define the mass fraction of the ABC as  $f_{abc} = \rho_{cl} / \rho_{\text{out}}$  which determines the energy release to the cosmic plasma at the epoch right before and during hydrogen recombination. Because of Compton and bremsstrahlung interactions the energy density of the products of annihilation leads to the CMB energy

spectrum distortion in different ways [12, 13]. If  $\tau_{ev}$  corresponds to the redshift  $z > 3 \times 10^5 (\Omega_b h^2 / 0.022)^{-1/2}$  then we should get a Bose-Einstein spectrum

$$n(x, \mu) = [\exp(x + \mu) - 1]^{-1}, \quad (14)$$

where  $x = h\nu/kT$  (here  $h$  is the Planck constant, not the Hubble constant),  $\nu$  is the frequency of the photons,  $\mu$  is the chemical potential:

$$\mu = \mu_0 \exp(-2x_0/x) \quad (15)$$

where  $x_0 = 0.018 (\Omega h^2 / 0.125)^{7/8}$ . It has been shown [12] that chemical potential  $\mu$  is related with the energy release from annihilation by  $\mu = 3\rho_{abc} c^2 / 2\varepsilon_r$ , where  $\varepsilon_r = 4\pi/c \int I(\nu) d\nu$  and  $I(\nu)$  is intensity of the CMB. For the redshift of annihilation below  $z = 3 \times 10^5 (\Omega_b h^2 / 0.022)^{-1/2}$  the distortions of the CMB power spectrum follows to  $y$ -parameter type [14]:

$$n(x) = \frac{1}{\sqrt{4\pi y}} \int d\xi \frac{\exp[-(\ln x + 3y - \xi^2)/4y]}{\exp(\xi) - 1} \quad (16)$$

where

$$y = \int_0^z \frac{k(T_e - T_{cmb})}{m_e c^2} \sigma_T n_e(z) c \frac{dt}{dz} dz \quad (17)$$

and  $\sigma_T$  is the Thomson cross-section,  $n_e$  and  $T_e$  are the electron number density and temperature, respectively. The magnitude of  $y$ -distortion is related to the total energy transfer by  $\kappa = \Delta E / \varepsilon_r = \rho_{abc} c^2 / \varepsilon_r = \exp(4y) - 1$ . At the epoch  $10^3 \leq z \leq 10^4$  the COBE FIRAS data give the constraint of the energy release from annihilation  $\kappa \leq 2 \times 10^{-4}$ , while  $y \leq 1.5 \times 10^{-5}$ , and  $\mu_0 \leq 9 \times 10^{-5}$  at 95% CL [7, 8, 9].

We would like to point out that the above mentioned properties of the spectral distortions on the CMB power spectrum is based on the assumption that the distribution of the anti-baryonic matter is spatially uniform without any clusterization, and therefore, no additional angular anisotropy and polarization of the CMB would have been produced during the epoch of hydrogen recombination. However, cloudy structure of the spatial distribution of anti-matter zones would generate spatial fluctuation of the  $y$ -parameters, similar to the Sunyaev-Zeldovich effect from the hot gas in clusters of galaxies at relatively higher redshift  $\sim z_{\text{rec}}$ . Moreover, such clouds would produce relatively higher but localized  $y$ -distortions on the CMB power spectrum, which corresponds, in mean, to the COBE FIRAS limit but locally could be much higher.

### ELECTROMAGNETIC CASCADES AND THE HYDROGEN RECOMBINATION

As in previous section, below we want to estimate possible influence of the electromagnetic products of annihilation on the ionization balance at the epoch of the

hydrogen recombination. Using quantitative approach, we can assume that because of the energy transfer for the photons from  $E \sim m_p c^2$  down to  $E \sim I = 13.6\text{eV}$ , where  $I$  is the ionization potential, some fraction  $x_e \leq 1$  could be reionized by the non-equilibrium quanta from the electromagnetic cascades in the plasma. The energy balance for such ionization follows

$$I x_e n_{bar} \simeq \omega \varepsilon_r \kappa|_{z \sim z_{rec}} \quad (18)$$

where  $\omega$  is the efficiency of the energy transforms down to the ionization potential range and  $z_{rec} \simeq 10^3$ . From Eq.(18) one obtains

$$\omega \leq 5.4 \times 10^{-6} \left( \frac{\Omega_b h^2}{0.022} \right) \left( \frac{1+z}{1000} \right)^{-1} \left( \frac{\kappa}{2 \times 10^{-4}} \right)^{-1} \left( \frac{x_e}{0.1} \right) \quad (19)$$

Thus, the relatively small fraction ( $\sim 10^{-5}$ ) of the annihilation energy release can distort the kinetics of the cosmological hydrogen recombination. The concrete mechanism of the energy transition, starting from  $E \simeq m_p c^2 \sim 1\text{ GeV}$  down to  $E \sim I$  is connected with the electromagnetic cascades of the annihilation products with cosmic plasma. The annihilation of a nucleon and an antinucleon produces  $\sim 5$  pions, 3 of which are charged [15]. For charged pions, electromagnetic cascade appears due to  $\pi^{(+,-)} \rightarrow \mu^{(+,-)} + \nu_\mu^{(-,+)}$  decay including  $\mu^{(+,-)} \rightarrow e^{(+,-)}$  transition. The neutral pions decay into two photons  $\pi^0 \rightarrow 2\gamma$ . About 50% of the energy release is carried away by the neutrino, about 30% by the photons and about 17% by electrons and positrons [16]. The spectrum of the decay has an exponential shape  $n(E) \propto \exp(-E/E_0)$ , where  $E \geq E_0 \simeq 70\text{ MeV}$  [15]. For the electron-positron pair and  $\gamma$ -quanta the leading process of the energy redistribution down to ionization potential are Compton scattering by the CMB photons and the electron-positron pair production  $\gamma + (H, He) \rightarrow (H, He) + e^+ + e^-$ . When  $E \gg m_e c^2$ , the Compton cross-section is well approximated by the Klein-Nishina formula [17]

$$\sigma_C \simeq \frac{3}{8} \sigma_T \left( \frac{m_e c^2}{E} \right) \left[ \ln \left( \frac{2E}{m_e c^2} \right) + \frac{1}{2} \right], \quad (20)$$

where  $\sigma_T$  is the Thomson cross-section. The corresponding optical depth for the Compton scattering is  $\tau_C \simeq 2.1 \sigma_T (m_e c^2 / E_0) \simeq 7.5 \times 10^{-3} \tau_T$ , where

$$\sigma_T = 56.7 \left( \frac{\Omega_b h^2}{0.022} \right) \left( \frac{\Omega_m h^2}{0.125} \right)^{-1/2} \left( \frac{1+z}{1000} \right)^{3/2} \quad (21)$$

For the inverse Compton scattering of high energy electrons by the CMB photons the corresponding optical depth is  $\tau_{IC} \simeq 2 \times 10^9 \left( \frac{\Omega_b h^2}{0.022} \right) \tau_C \gg 1$  for  $z \simeq 10^3$ .

The pair production cross-section  $\sigma_{pc}$  has the following asymptotic for  $w = E/m_e c^2 > 6$  [18]

$$\sigma_{He} \simeq 8.8 \alpha_f r_0^2 \ln \left( \frac{513w}{825+w} \right) \quad (22)$$

for neutral helium and

$$\sigma_H \simeq 5.4 \alpha_f r_0^2 \ln \left( \frac{513w}{825+w} \right) \quad (23)$$

for the neutral hydrogen, where  $r_0^2 = \frac{3}{8\pi} \sigma_T$  and  $\alpha_f$  is the Fermi constant. Note that for ionized hydrogen-helium which contain 76% and 24% of corresponding mass fractions of the light elements, the optical depth is close to

$$\tau_{pc} \simeq 2.3 \left( \frac{\Omega_b h^2}{0.022} \right) \left( \frac{\Omega_m h^2}{0.125} \right)^{-1/2} \left( \frac{1+z}{1000} \right)^{3/2}, \quad (24)$$

for  $wz \gg 825$  [18].

Thus, as one can see from Eq.(21)-(24), the energy loss for high-energy electrons is determined by the inverse Compton scattering off the CMB photons, whereas for the high-energy photons the main process of the energy loss is the electron-positron pair creation by neutral and ionized atoms.

For the non-relativistic electrons ( $w < 1$ ) the optical depth inverse Compton scattering is given by  $\tau_{IC} \simeq 2 \times 10^9 \tau_T$ , whereas for the photons it is close to the Thomson optical depth. It has been shown [17, 18] that for high energy  $\rightarrow$  low energy photons conversion the spectral number density is

$$\frac{dn(E)}{dE} \simeq \frac{A}{\sigma_T n_e c} \left( w^{-2} + \frac{14}{5} w^{-1} \right) \quad (25)$$

for  $E < E_0$ , which corresponds to energy density

$$\epsilon = \int E dE \frac{dn(E)}{dE} \simeq \frac{14 A m_e c E_0}{5 n_e \sigma_T} \left[ 1 + \frac{5}{14} \left( \frac{m_e c^2}{E_0} \right) \right]. \quad (26)$$

Therefore, from Eq.(25)-(26) we can estimate the spectral energy density at the range  $E \simeq I$

$$\epsilon(E \simeq I) \simeq \frac{5}{14} \ln 2 \cdot \epsilon \frac{m_e c^2}{E_0} \simeq 1.7 \times 10^{-3} \epsilon, \quad (27)$$

which is much higher than the limit from Eq.(19). Note that an additional factor 0.47 results from the fraction of the annihilation energy related to electromagnetic component.  $\omega \simeq 8 \times 10^{-4}$ . As one can see, the non-equilibrium ionization of the primordial hydrogen and helium at the epoch of recombination is more effective than the distortions of the CMB blackbody power spectra.

## DISTORTION OF THE RECOMBINATION KINETICS

The model of the hydrogen-helium recombination process affected by the annihilation energy release can be described phenomenologically in terms of the injection

of additional  $Ly_\alpha$  and  $Ly_c$  photons [19, 20, 21]. For the epochs of antimatter clouds evaporation ( $\eta - 1 \ll 1$ ) the rate of ionized photon production  $n_\alpha$  and  $n_c$  are defined as

$$\begin{aligned} \frac{dn_\alpha}{dt} &= \varepsilon_\alpha(t) \langle n_b(t) \rangle H(t), \\ \frac{dn_i}{dt} &= \varepsilon_i(t) \langle n_b(t) \rangle H(t), \end{aligned} \quad (28)$$

where  $H(t)$  and  $\langle n_b(t) \rangle$  are the Hubble parameter and the mean baryonic density, respectively,  $\varepsilon_{\alpha,i}(t)$  are the efficiency of the  $Ly_\alpha$  and  $Ly_c$  photon production. As one can see from Eq. (28) the dependence of  $\varepsilon_{\alpha,i}(t)$  parameters upon  $t$  (or redshifts  $z$ ) allows us to model any kind of ionization regimes. For the ABC from Eq.(19)-(20) we have

$$\varepsilon_{\alpha,i} \simeq \omega \left( \frac{m_p c^2}{I} \right) [H(t) \tau_{ev}]^{-1} f_{abc}. \quad (29)$$

If the time of evaporation is comparable with the Hubble time  $H^{-1}(t)$  at the epoch of recombination  $z \sim z_{\text{rec}}$ , then  $\varepsilon_{\alpha,i}$  parameters are constant and proportional to  $f_{abc}$ .

We demonstrate the effectiveness of our phenomenological approach in Fig. 1: the ionization fraction  $x_e$  against redshift for the three models listed below:

- model 1:  $\varepsilon_\alpha \simeq \varepsilon_i = 1$ ;
- model 2:  $\varepsilon_\alpha \simeq \varepsilon_i = 10$ ;
- model 3:  $\varepsilon_\alpha \simeq \varepsilon_i = 100$ .

The curves are produced from the modification of the RECFAST code [22]. For all models we use the following values of the cosmological parameters:  $\Omega_b h^2 = 0.022$ ,  $\Omega_m h^2 = 0.125$ ,  $\Omega_\lambda = 0.7$ ,  $h = 0.7$ ,  $\Omega_m + \Omega_\lambda = 1$ ,  $H(t) \tau_{ev} \sim 1$ .

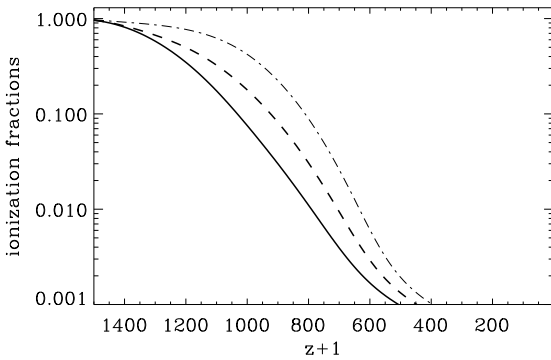


FIG. 1: The ionization fractions for the model 1 (the solid line), the model 2 (dash line) and model 3 (dash-dot line) as a function of redshift.

As one can see from Fig. 1 all the models 1-3 produce delays of recombination and can distort the CMB

anisotropy and polarization power spectrum, which we will discuss in the following Section. We would like to point out that our assumption about the characteristic time of the ABC evaporation, namely  $H(t_{\text{rec}}) \tau_{ev} \sim 1$  implies that at  $t \gg t_{\text{rec}}$  all the ABC disappear. If  $H(t_{\text{rec}}) \tau_{ev} \gg 1$ , however, at the epoch of recombination the corresponding influence of the non-equilibrium photons can be characterized by the renormalization of the  $\varepsilon_{\alpha,i}$  parameters in the following way:  $\varepsilon_{\alpha,i}(z) = \varepsilon_{\alpha,i}(z_{\text{rec}}) (H(z) \tau_{ev})^{-1}$  where  $\varepsilon_{\alpha,i}(z_{\text{rec}})$  corresponds to the models 1-3. The mean factor, which should necessarily be taken into account, is the absorption of the high energy quanta from annihilation by the CMB photons. If, for example,  $\tau_{ev}$  corresponds to the redshift  $z_{\text{rei}} \sim 100$ , then

$$\varepsilon_{\alpha,i}(z_{\text{rec}}) \simeq \varepsilon_{\alpha,i}(z_{\text{rec}}) \left( \frac{z_{\text{reion}}}{z_{\text{rec}}} \right)^{3/2} \sim 0.03 \varepsilon_{\alpha,i}(z_{\text{rec}}). \quad (30)$$

For the relatively early reionization of the hydrogen by the products of annihilation, the ionization fraction of matter  $x_e = n_e / \langle n_b \rangle$  can be obtained from the balance between the recombination and the ionization process

$$\frac{dx_e}{dt} = -\alpha_{\text{rec}}(T) \langle n_b \rangle x_e^2 + \varepsilon_i(z) (1 - x_e) H(z) \Theta(z_{ev} - z), \quad (31)$$

where  $\alpha_{\text{rec}}(T) \simeq 4 \times 10^{-13} (T/10^4 \text{K})^{-0.6}$  is the recombination coefficient,  $z_{ev}$  corresponds to  $\tau_{ev}$  and  $T$  is the temperature of the plasma and  $\langle n_b \rangle = n_b$  is the mean value of the baryonic number density of the matter. In an equilibrium between the recombination and the ionization process the ionization fraction of the matter follows the well-known regime

$$\frac{x_e^2(z)}{1 - x_e(z)} = \frac{\varepsilon_i(z) H(z)}{\alpha_{\text{rec}}(z) n_b(z)} \Theta(z_{ev} - z), \quad (32)$$

where  $H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + 1 - \Omega_m}$  and  $n_b \simeq 2 \times 10^{-7} (\Omega_b h^2 / 0.02) (1+z)^3$ . We would like to point out that Eq.(32) can be used for any models of the late reionization, choosing the corresponding dependence of the  $\varepsilon_i(z)$  parameter on redshift. This point is vital in our modification of the RECFAST and the CMBFAST packages, from which we can use the standard relation for matter temperature  $T(z) \simeq 270 (1 + z/100)^2 \text{K}$  and all the temperature peculiarities of the reionization and clumping would be related with the  $\varepsilon_i(z)$  parameter through the mimicking of ionization history [23, 24].

From Eq.(32) one can find the maximal value of the ionization fraction at the moment  $z \simeq z_{ev}$

$$x_e^{\text{max}} = -\frac{1}{2} \Gamma + \left( 1 + \frac{1}{4} \Gamma^2 \right)^{1/2} \quad (33)$$

where  $\Gamma = \varepsilon_i(z_{ev}) H(z_{ev}) / [\alpha_{\text{rec}}(z_{ev}) n_b(z_{ev})]$ . At  $10 \ll z < z_{ev}$  the relaxation of the matter temperature to the

CMB temperature proceeds faster than the ionized hydrogen becoming neutral and for  $x_e$  from Eq.(31) we get

$$x_e(t) \simeq x_e^{\max} \left( 1 + x_e^{\max} \int_{\tau_{ev}}^t \alpha(T) n_b dt \right)^{-1}. \quad (34)$$

While the temperature of matter is close to the CMB temperature  $T_{\text{CMB}}$ , the corresponding time of recombination is

$$\Delta t_{\text{rec}} \simeq \frac{x_e}{|dx_e/dt|} \simeq (x_e^{\max})^{-1} t_{\text{rec}}(T_{\text{CMB}}), \quad (35)$$

where  $t_{\text{rec}} = [\alpha(T) n_b]^{-1} \ll \tau_{ev}, H^{-1}(t)$ .

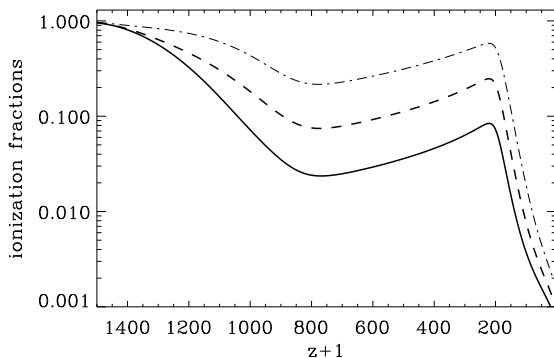


FIG. 2: The ionization fractions for the model 4 (the solid line), the model 5(dash line) and model 6 (dash-dot line) as a function of redshift.

In addition to the models 1-3 we introduce the following three models:

- model 4:  $\varepsilon_\alpha \simeq \varepsilon_i = 0.1 \times [(1+z)/1000]^{3/2}$ ;
- model 5:  $\varepsilon_\alpha \simeq \varepsilon_i = 1 \times [(1+z)/1000]^{3/2}$ ;
- model 6:  $\varepsilon_\alpha \simeq \varepsilon_i = 10 \times [(1+z)/1000]^{3/2}$ .

where  $z_{ev} = 200$ . In Fig.3 we plot the ionization fraction for the models 4-6 versus redshift. As one can see from the Fig.3 the delay of recombination at  $z = 10^3$  is smaller than in Fig.1, but the reionization appears at  $z \simeq z_{ev}$ . At the range of redshifts  $z \gg z_{ev}$  the behavior of ionization fraction follows Eq.(34) with rapid decrease. The properties of the models 4-6 are similar to those of the peak-like reionization model [24].

## THE CMB ANISOTROPY AND POLARIZATION FEATURES FROM THE MATTER-ANTIMATTER ANNIHILATION

In order to find out how sensitive is the polarization power spectrum to the annihilation energy release,

we consider phenomenologically different variants of hydrogen reionization models by modifying the CMBFAST code for the models 1-6 [25]. One additional problem appears if we are interested in observational constraints on the anti-matter fraction abundance related to the late reionization of hydrogen at low redshift  $z < 20$ . After *WMAP* mission the most preferable value of the optical depth of reionization is  $\tau_{\text{reion}} \simeq 0.17$  [26], while it is also shown [24] that even the “standard model” with  $z_{\text{reion}} = 6$  is not ruled out from the *WMAP* data (see also [36]). Recently it has been argued that the late reionization could exist with two stages, one at  $z_{\text{reion}} \simeq 15$  and  $z_{\text{reion}} \simeq 6$  due to energy release from different population of stars [28] or heavy neutrinos [29]. Without measurements with higher accuracy of the CMB polarization and temperature-polarization cross-correlation, it is unlikely to settle the issue on late reionization, even for *WMAP* resolution and sensitivity. However, any assumption about the optical depth of the late reionization are crucial for the estimation of any constraints on the ABC abundance. If, for example, we adopt the *WMAP* limit  $\tau_{\text{reion}} \simeq 0.17$  from the pure late reionization, the peak-like or delayed recombination models from the ABC would be restricted very effectively. But, if we assume that roughly  $\tau_{\text{reion}} \sim 0.04$  comes from late reionization and  $\tau_{\text{reion}} \sim 0.06 \div 0.12$  is related to the ABC contamination at relatively high redshifts, then the constraints on the ABC abundance would be rather smaller than for the previous case. For estimation of the ABC features in the CMB anisotropy and polarization power spectrum we use a more conservative limit on the optical depth of reionization  $\tau_{\text{reion}} \sim 0.04$  at  $z_{\text{reion}} \simeq 6$  in order to obtain the upper limit on the ABC manifestation in the CMB data.

In Fig. 5 we plot the polarization power spectrum  $C_p(\ell)$  for the model 1 -6 plus the standard single reionization model at  $z_{\text{reion}} \simeq 6$ . The difference between model 1 and 2 mainly lies in the multipoles  $2 < \ell < 30$ .

As one can see from the Fig.4, in order of the magnitude the  $\varepsilon_{\alpha,i}$  parameters should be smaller than unity, if  $z_{ev} \simeq z_{\text{rec}}$  and  $\varepsilon_{\alpha,i} < 10^{-2}$ , if  $z_{ev} \simeq 200$ . So, using Eq.(29) one can find that

$$f_{abc} = \omega^{-1} \varepsilon (H(t) \tau_{ev}) \frac{I}{m_p c^2} \leq 1.7 \times 10^{-5} \left( \frac{1+z_{ev}}{200} \right)^{3/2}, \quad (36)$$

while from the spectral distortion of the CMB blackbody power spectra we obtain

$$f_{abc}^y \leq 1.7 \times 10^{-4} \left( \frac{\Omega_b h^2}{0.022} \right) \left( \frac{1+z_{ev}}{200} \right) \quad (37)$$

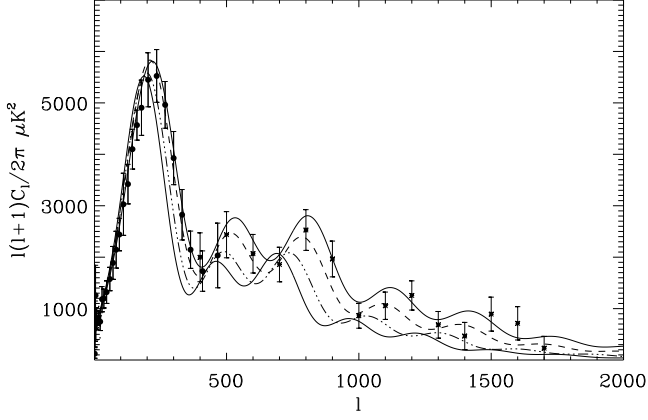


FIG. 3: The CMB power spectrum for the standard model without energy injection, (the solid line), the model 1 (the dash line), model 2 (the dash-dot line) and model 3 (the lowest thick solid line) as a function of redshift. For  $\ell < 500$  we use the *WMAP* data [30], while for  $\ell > 500$  together with error bars the data is from *CBI* experiment [31].

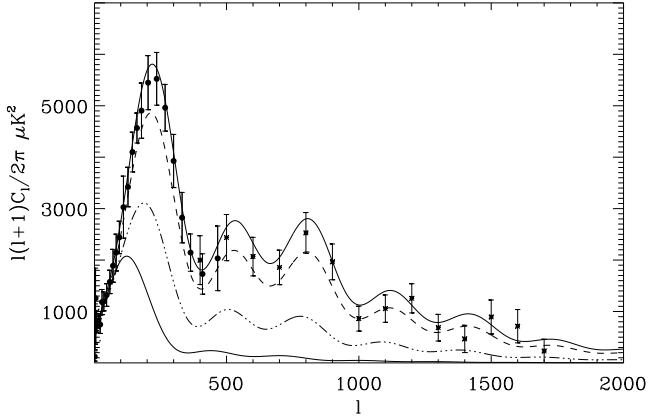


FIG. 4: The CMB power spectrum for the standard model without energy injection (the solid line), the model 4 (dash line), 5 (dash-dot line) and 6 (the lowest thick solid line) as a function of redshift. The experimental data points are the same as in Fig.3.

### HOW *PLANCK* DATA CAN CONSTRAIN THE MASS FRACTION OF THE ANTIMATTER?

As is mentioned above, the observational constraint on the antimatter mass fraction  $f_{abc}$  depends on the accuracy of the power spectrum estimation from the contemporary and upcoming CMB data sets. As an example, how the upcoming *Planck* data would be important for cosmology, we would like to compare the upper limit on the  $f_{abc}$  parameter, using the *WMAP* and *CBI* data with the expected sensitivity of the *Planck* data. We assume that all the systematic effects and foreground contami-

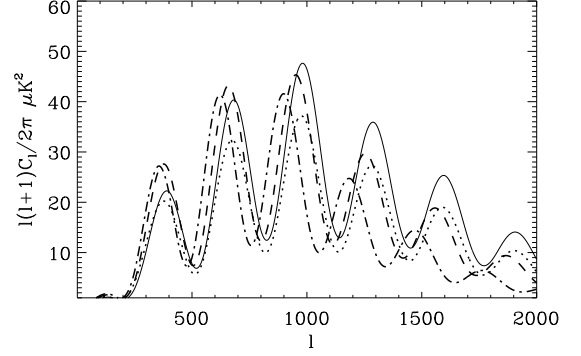


FIG. 5: The polarization power spectrum for the standard model (the solid line), the model 4 (the dot line), the model 2 (the dash line) and the model 3 (the dash-dot line) as a function of redshift.

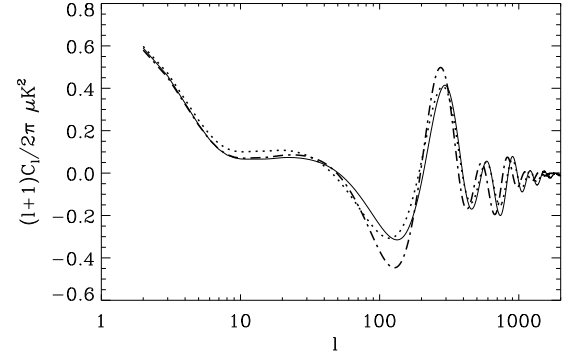


FIG. 6: The TE cross-correlation power spectrum for the models listed in Fig.5 with the same notations.

nations should be successfully removed and the accuracy of the  $C_\ell$  estimation would be close to the cosmic variance limit at low multipoles for both the temperature anisotropies, polarization and the TE cross-correlation as well.

The differences between the delayed recombination and early reionized universe models in comparison with the expected sensitivity of the *Planck* experiment can be expressed in terms of the power spectrum  $C^{a,p}(\ell)$  (for the anisotropy, and the  $E$  component of polarization) [21]

$$D_{i,j}^{a,p}(\ell) = \frac{2 [C_i^{a,p}(\ell) - C_j^{a,p}(\ell)]}{C_i^{a,p}(\ell) + C_j^{a,p}(\ell)}, \quad (38)$$

where the indices  $i$  and  $j$  denote the different models and  $a$  and  $p$  denote anisotropy and polarization. In order to clarify the manifestations of the complex ionization regimes in the models 1 and 4 we need to compare the peak to peak amplitudes of the  $D_{i,j}^{a,p}(\ell)$  function with

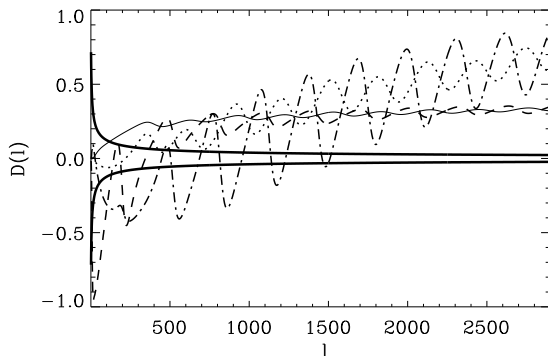


FIG. 7: The  $D_{i,j}^{a,p}(\ell)$  function for different models of ionization. The solid line corresponds to  $D_{i,j}^a(\ell)$  for  $i = 0$  (standard model without the ABC) and  $j = 4$ ; the dot line is  $D_{i,j}^a(\ell)$  for  $i = 0$  and  $j = 1$ ; the dash line corresponds to  $D_{i,j}^p(\ell)$  for  $i = 0$  and  $j = 4$ ; the dash-dot line is  $D_{i,j}^p(\ell)$  for  $i = 0$  and  $j = 1$ . The thick solid lines represent the error bars limit from cosmic variance.

the expected error of the anisotropy power spectrum for *Planck* experiment. We assume that the systematics and foreground effects are successfully removed. The corresponding error bar should be

$$\frac{\Delta C_\ell}{C_\ell} \simeq \frac{1}{\sqrt{f_{\text{sky}}(\ell + \frac{1}{2})}} [1 + w^{-1} C_\ell^{-1} W_\ell^{-2}], \quad (39)$$

where  $w = (\sigma_p \theta_{\text{FWHM}})^{-2}$ ,  $W_\ell \simeq \exp[-\ell(\ell+1)/2\ell_s^2]$ ,  $f_{\text{sky}} \simeq 0.65$  is the sky coverage during the first year of observations,  $\sigma_p$  is the sensitivity per resolution element  $\theta_{\text{FWHM}} \times \theta_{\text{FWHM}}$  and  $\ell_s = \sqrt{8 \ln 2} \theta_{\text{FWHM}}^{-1}$ .

As one can see from Fig. 7 for  $D_{i,j}^{a,p}(\ell)$  the corresponding peak to peak amplitudes are at the order of magnitude  $5 \div 10$  times higher than the error bars limit at  $\ell \sim 1500 \div 2500$ . That means that both anisotropies and the polarization power spectra caused by the complicated ionization regimes can be tested directly for each multipole of the  $C_\ell$  power spectrum by *Planck* mission, if the systematic effects are removed down to the cosmic variance level. Moreover, at the 95% CL the corresponding constraint on the  $f_{abc}$  parameter can be  $2.5 \div 5$  times smaller than the limit from Eq.(36), or in principle, the upcoming *Planck* mission should be able to detect any peculiarities caused by the antimatter annihilation during the epoch of the hydrogen recombination.

It is worth noting that in this paper we do not discuss the direct contribution of antimatter regions to the CMB anisotropy formation, assuming that their corresponding size is smaller than the typical galactic scales, and also smaller than the corresponding angular resolution of the recent CMB experiments such as *WMAP*, *CBI*, *ACBAR*. If the size of the ABC is comparable with the size of

galactic or cluster scales, they could manifest themselves as point-like sources in the CMB map. For the upcoming *Planck* mission there are well defined predictions for the number density of bright point sources for each frequency band at the range  $30 \div 900$  GHz. It would be interesting to obtain a new constraint on the ABC fraction for large-scale clouds. This work is in progress.

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